



Particle Test Fluence: What's the Right Number?

Kenneth A. LaBel
ken.label@nasa.gov

**Co-Manager, NASA Electronic Parts and Packaging
(NEPP) Program**

This work is supported by the NEPP Program

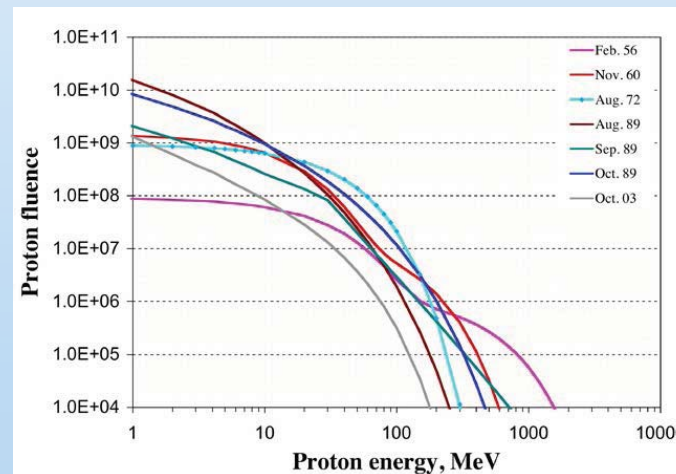


Acronyms

Acronym	Definition
DUT	Device Under Test
F	Fluence
Gbit	Gigabit
IEEE	Institute of Electrical and Electronics Engineers
LET	linear energy transfer ($\text{MeV}\cdot\text{cm}^2/\text{mg}$)
MeV	million electronvolts
NEPP	NASA Electronic Parts and Packaging
POF	Physics of Failure
SEE	Single Event Effect
SEFI	Single Event Functional Interrupt
SEL	Single-Event Latchup
SEU	Single Event Upset
SOC	Systems on a Chip
TNS	Transactions on Nuclear Science

Outline

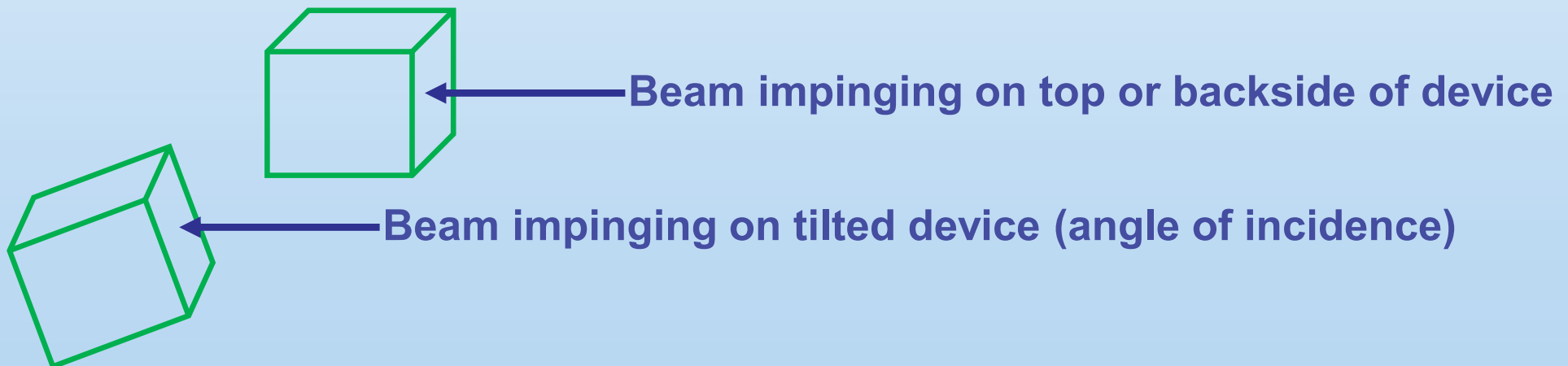
- **What's fluence?**
 - Brief history lesson
- **The factors that influence fluence levels:**
 - Mission environment and particle kinematics,
 - Number of samples being used in flight,
 - Number of transistors/nodes, and
 - Number of dynamic operating states.
- **Considerations and implications**
- **Summary**



<http://journalofcosmology.com/images/StraumeFigure3a.jpg>

What's All This Fluence Stuff, Anyhow?

- **Fluence is:**
 - The number of particles impinging on the surface of a device during a single ion beam test run normalized to a square centimeter. Denoted F .
- **It is NOT:**
 - *Cumulative fluence*: the sum of all individual fluence levels for all beam runs (usually only for a given ion, energy, and angle).
 - *Effective fluence*: beam run fluence normalized by $\cos(\theta)$, where θ is the angle of incidence.





Motivation

- **Assumption: dynamic operations**
- **Each transistor and operating-state has the same random probability of getting hit.**
 - That's the challenge: **single event effects (SEE) are random* processes.**
 - In other words, the error signature will be a function of where a particle hits and when a particle hits in a dynamic operating system.
- **Testing is an attempt to quantify this random process and provide:**
 - Some reasonable coverage of the possible error signatures by getting sufficient particles to provide confidence in coverage of the transistor/state space.
- **For a billion-transistor, complex, system on a chip (SOC) device, how do we ensure this?**
 - This is the crux of this talk: doing enough testing to have a reasonable level of confidence.

**Okay, it's really a Markov process –
whether the occurrence of an SEU in the future and past are independent.*

Tradition: When Do We Stop a Test at the Particle Beam?



- Existing test standards provide guidance on setting a “beam stop” at either a given fluence or specific number of events.
- Fluence is (number of particles)/cm² for a given test run
- JESD57* (the long time guidance for heavy ion SEE) gives recommendations of:
 - A fluence of 1×10^7 particles/cm², or
 - 100 events, or
 - Significant event (such as SEFI or SEL).
- Proton testing is often stopped at a fluence of 1×10^{10} protons/cm² (or 100 errors or a significant event).
- Are these numbers taking into account:
 - Physics of failure (POF),
 - Circuit operation, and
 - Sufficient statistics?

** JEDEC JESD57: Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation, Revised 1996*

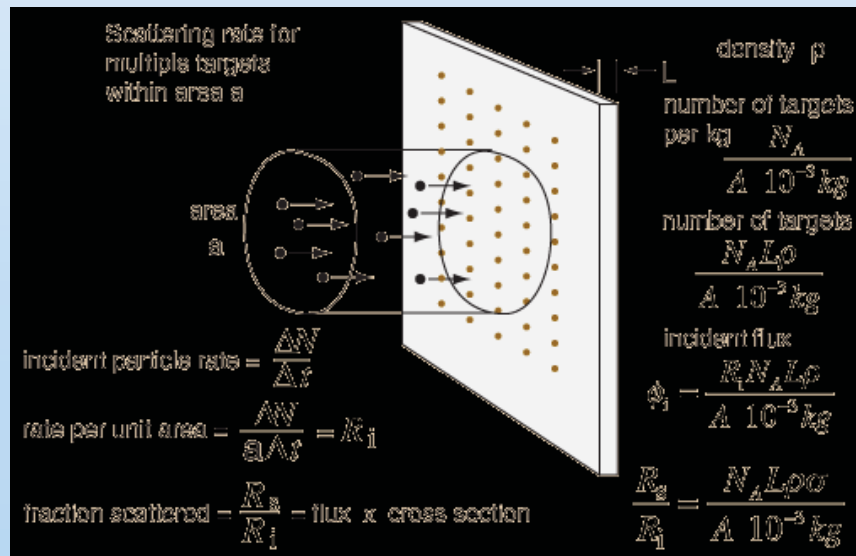


The Challenges

- There are four basic considerations for determining fluence levels:
 - Geometry:
 - The number of potentially sensitive nodes or transistors in the device (statistical node coverage).
 - Operation (and propagation):
 - The dynamic operation of the device under test (statistical state and error propagation coverage).
 - Sample size:
 - The number of samples of the device being used in the system (statistical system coverage).
 - POF and (more) statistics:
 - The environment exposure and particle kinematics (i.e., what happens when a particle strikes the semiconductor).
- *Note, for dynamic operations we are often looking not only at measuring a cross-section, but determining as many possible error signatures as reasonable.*
 - *A simple example is the range of transients induced in an amplifier.*

Gee, I'm a Tree!

- This is the simplest of the challenges to discuss. So consider,
 - If a memory device under test (DUT) has a billion bits (Gbit), how many random particle strikes on the die surface are required to cover a sufficient number of potentially sensitive bits in order to obtain good statistics?
 - 1%?, 10%?, 50%?, 100%?
 - Ask yourself, what is the objective?
 - Mean distribution?
 - Corner cases?
 - Suggest 10% at a minimum, but...
 - Remember there's timing involved (more to come next)...



<http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/imgnuc/crosec.gif>

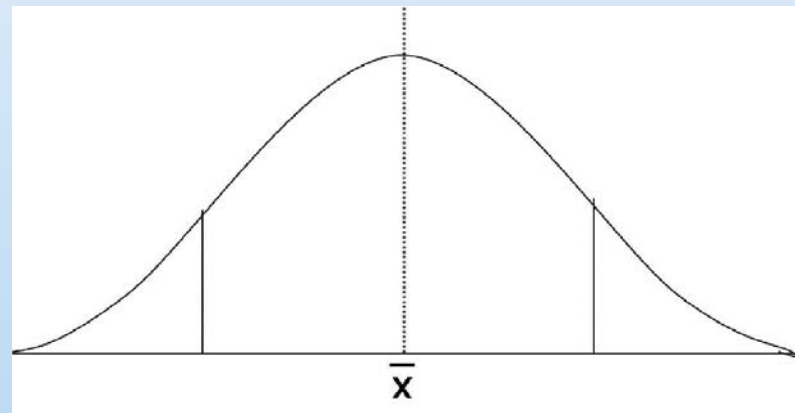


Dynamic Operation Constraints

- **State space issues: Assume that a particle strikes a specific location (sensitive node). What can happen?**
 - An error can occur immediately,
 - An error can occur at a undetermined time (and/or location) later, or
 - Nothing.
- **Why? Let's look at that Gbit memory.**
 - How long might it take to cycle through the device memory space? Maybe a minute or so? Is it a simple form of propagation?
 - What if I'm writing over the memory space? Is it possible to clear errors by re-write and never detect them?
- **Take, for example (courtesy Melanie Berg), a 32-bit counter.**
 - There are 2^{64} states.
 - Operational frequency of 50 MHz (20 nsec per state) – over 300 billion seconds to cover all states.
 - Not happening during a beam run.
 - Key is understanding the error signature space and propagation effects... (ask Melanie about "Test Like You Fly" - not always best).
 - Remember, each state has the same random chance of taking a hit.
 - Consider a truly complex device like a system on a chip.
- ***Operating state coverage (statistics), and error signatures.***

(Sample) Size Matters

- Besides the usual discussion of statistical relevance of samples from a single wafer lot, consider what the test results will be applied to.
 - How many samples in the flight application are being used?
 - There's a big difference between flying two samples of a device and one thousand!
 - Outlier results are important when device is being used extensively. [1]
- It's also important to grasp the idea of limiting cross-section (i.e., no events observed).



How important is knowing outliers in SEE testing?

[1] K.A. LaBel, A.H. Johnston, J.L. Barth, R.A. Reed, C.E. Barnes, "Emerging Radiation Hardness Assurance (RHA) Issues: A NASA Approach for Space Flight Programs," IEEE Trans. Nucl. Sci., Vol. 45, No.6, pp. 2727-2736, Dec. 1998.

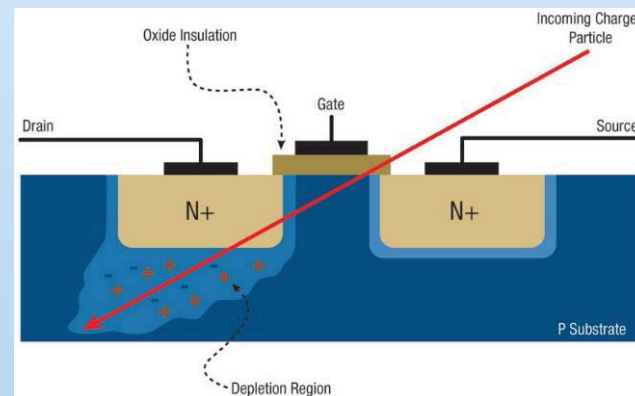


Application Environment

- **Rule #1: Ground irradiation is a confidence test and not a precise risk definition process.**
 - The test is being performed to “bound” a problem. In other words,
 - Test fluence levels are not meant to be the same as what a device will be exposed to, but to provide confidence that the risk will be less than X of occurring.
 - Remember, X can be based on a limiting cross-section when no events have been observed
 - Though not likely true, assume that the next particle that hits the DUT causes an event, so that the limit of the cross-section is $\sim 1/F$.
 - It is important to remember that a test fluence of two to ten times a mission predicted fluence only goes so far in reducing risk.
 - Higher levels should be considered (keeping in mind total dose concerns at the DUT level) for better risk reduction.
 - If a mission proton fluence (of energies of interest) is 10^9 , what does a test to 10^{10} buy?

More on POF

- **Not all particles are created equal:**
 - Some deposit energy “on a track” as per image below.
 - Some interact with materials and cause secondary particles to deposit the energy.
 - This is the traditional proton SEU concern (though direct ionization with low energy protons is a consideration for advanced technology nodes).
 - This is a lesser concern for heavy ions though it shouldn't be ignored.
- **So what's this have to do with fluence levels?**



http://www.cotsjournalonline.com/files/images/1896/cots1201_Mic_Fig2_large.jpg

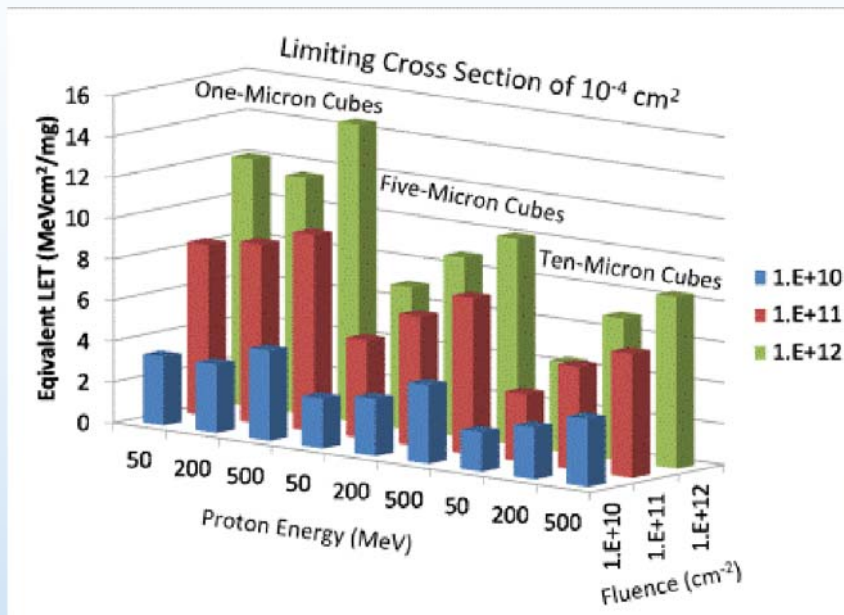


Proton Physics

- **Something on the order of 1 in 10^5 protons that hit a cm^2 of a silicon DUT interacts to cause a secondary particle.**
- **These secondary particles have a distribution of linear energy transfer (LET – hey, how'd I get so far in this talk without mentioning LET?) as well as usually being of short range.**
 - **These are particle kinematic effects to consider when establishing a proton fluence:**
 - Number of interactions,
 - Distribution of secondary ions, and
 - Risk coverage versus mission environment, sample size, etc...
 - **Is 10^{12} protons/ cm^2 a realistic choice?**
- ***Be wary of total dose or displacement damage at higher fluence levels: consider more samples of the DUT at lower fluence levels.***

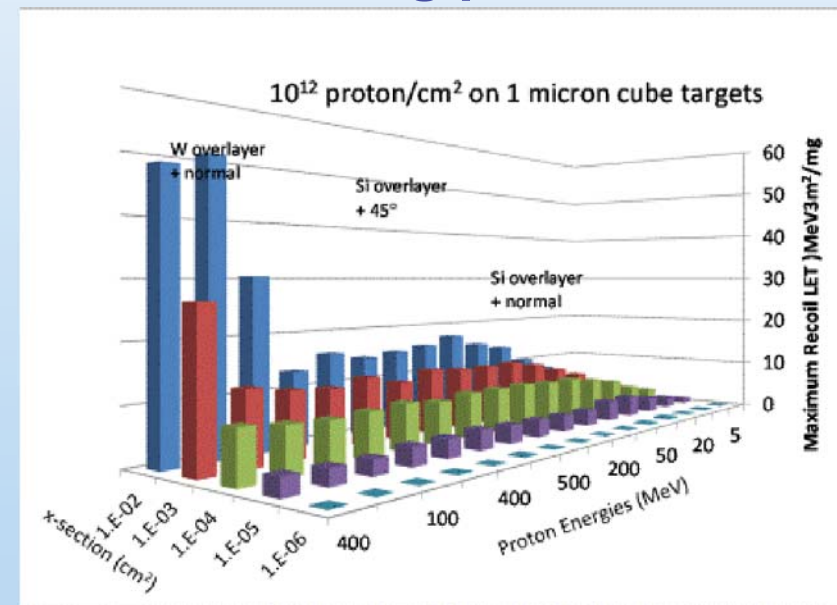
Visual Protons

(courtesy R. L. Ladbury and J.-M. Lauenstein, NASA/GSFC)



How good are protons at
simulating heavy ions?

Silicon's not the only culprit
In creating problems



And You Just Wanted a Number...



- **Sorry folks, there's no easy answer when you consider that:**
 - **F is a function of (geometry, operations, sample size, and POF).**
- **Suggestions:**
 - **Remember, it's a bounded problem and reducing risk is the desired outcome.**
 - **Risk can't fully be eliminated, but weeding out a reasonable coverage of error signatures and sensitivity levels is the goal.**
 - **Understand the dynamics of an accelerated beam test versus what you'll be exposed to in space:**
 - **Drives data collection and how to apply it.**
 - **Melanie Berg's "learning session" talk on Wednesday provides some thoughts on how you apply gathered data, but there are hidden gems that link with concerns noted here.**



Acknowledgements

- **Melanie Berg, ASRC Space & Defense**
- **Jean-Marie Lauenstein and Ray Ladbury, NASA/GSFC**